

Space-Based Gravity Detector for a Space Laboratory

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Abstract. A space-based superconducting gravitational low-frequency wave detector is considered. Sensitivity of the detector is sufficient to use the detector as a partner of other contemporary low-frequency detectors like LIGO and LISA. This device can also be very useful for experimental study of other effects predicted by theories of gravitation.

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1. Introduction

The problem of the registration of gravitational waves and investigation of their properties is too difficult to suppose that realization of the projects like LIGO will immediately solve all problems. When the detectors with high sensitivity will begin operate, the problems of identification of the signals will then appear. Under the surcumstances the using of other types of the detectors would be very useful. One of them is considered in this paper (See also [1], [2])

2. A Peculiarity of Magnetically Interacting Superconducting Solenoids

The detector is based on the a peculiarity of magnetically interacting superconducting solenoids that was discovered theoretically by a group of Ukrainian engineers [3].

Consider a pair of the superconducting solenoids A and B in line (Fig. 1) in the weightless state . If the solenoids carry the persistent currents I_1 and I_2 , it can be shown that the complete energy of the system is given by

$$U = (L_2 Q_1^2 - 2MQ_1 Q_2 - L_1 Q_2^2)/2D. \quad (1)$$

where L_1 and L_2 are the solenoids inductances , M is the mutual inductance of the solenoids that is the function of the distance x between the solenoids centers, $D = L_1 L_2 - M^2$, Q_1 and Q_2 are the constant fluxes in the solenoids.

The solenoids are attracted by the Ampere force $F = -\partial W/\partial x$ affecting the solenoids.

The peculiarity of this interaction is that at the condition $Q_1 \ll Q_2$ the Ampere force change its sign at some distance $x = x_0$ between the solenoids, and the function $W(x)$ has the minimum . At this position the solenoids in the weightless state are in a week stable equilibrium condition.

A typical dependence of the force F of the distance x (in CGS units) is given in Fig. 2 . The parameters of the solenoids are : the inductances are $1.15Hn.$, the lengths are $5cm.$, the radiuses are $5cm.$, $Q_1 = 1.15Wb$, $Q_2 = Q_1/100$.

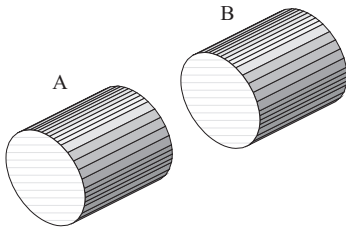


Figure 1. The solenoids in weightless state

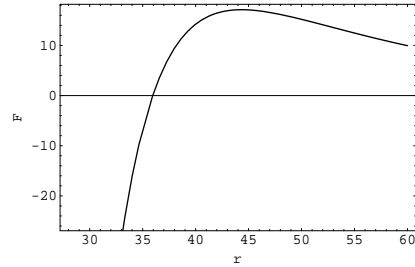


Figure 2. The Ampere force between the solenoids

Our experimental investigations confirm this result [2].

3. The Magnetically Coupled Solenoids as a Detector of Tidal Accelerations

Consider the properties of the system, formed by a pair of superconducting solenoids in weightless state, in the field of a gravitational wave with the frequency ν extending during the time interval t_0 perpendicularly to AB - direction. This system is a nonlinear oscillator, the small oscillations of which in AB - direction are described by the differential equation

$$m\ddot{q} + R(\dot{q}) + pq = f(t). \quad (2)$$

In eq.(2) $q = x - x_0$ is a small deviation from the equilibrium position, $\dot{q} = \partial q / \partial t$, $\ddot{q} = \partial^2 q / \partial t^2$, $R(\dot{q})$ is the air resistance, $p = U''(x_0)$ is the stiffness of the "magnetic spring", $f(t) = ma_g \sin(\omega t)$ at $0 < t < t_0$ and $f(t) = 0$ at $t > t_0$, m is the mass of the system, $\omega = 2\pi\nu$ and $a_g = \omega^2 h x_0 / 2$ is the amplitude of the tidal acceleration, caused by the gravitational wave.

If 1-type superconductors are used in the solenoids, the air resistance $R(\dot{q})$ is the key cause of the oscillations damping in the given system. For an ideal gas the function $R(\dot{q}) = -b\dot{q}|\dot{q}|$, where b , is a constant.

The typical sizes are: $R = 5 - 10 \text{ cm}$, $x = 30 - 40 \text{ cm}$, The proper frequency is less than 1 Hz and can reach 10^{-4} Hz .

Fig. 4 shows the response $q(t)$ (in CGS units system) of the detector to the gravitational wave with the dimensionless amplitude $h = 10^{-20}$ that shows Fig. 3.

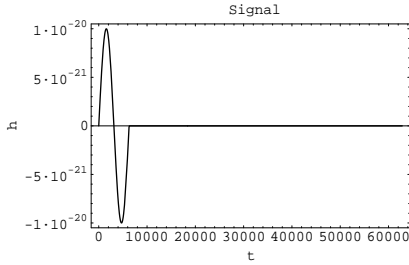


Figure 3. The signal

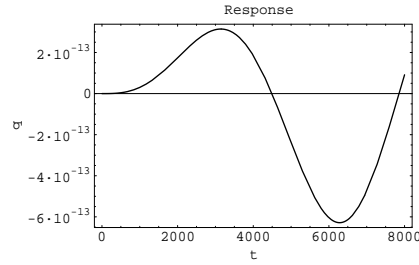


Figure 4. The detector response $q(t)$

4. Noises

The detector under study is a nonlinear oscillator. Using the Chandasekhar results concerning a linear oscillator and the method of the statistic linearization for the function $R(\dot{q})$ we have found that the the root-mean-square magnitude of the thermal fluctuations is : $\langle q^2 \rangle^{1/2} = \sigma_q$ where

$$\sigma_q^2(t) = \frac{4b^2}{(2\pi)^{1/2}m\omega_0^2} \frac{kT}{m} t^2 \left[1 - \frac{\sin^2(2\omega_0 t)}{2\omega_0^2 t^2} \right] \quad (3)$$

For example, if $m = 10^4 \text{ gm}$, $\nu_0 = 0.01 \text{ s}$, $t = 100 \text{ s}$, $b = 10^{-4} \text{ gm/cm}$, then the root-mean-square magnitude of the thermal fluctuations is : $\langle q^2 \rangle^{1/2} = 10^{-20} \text{ cm}$. Thus, in spite of the small mass the detector has a very low level of the thermal noise.

The inhomogeneity of the Earth and spacecraft gravitational fields leads to more serious problems. The tidal acceleration of the solenoids due to inhomogeneity of the Earth gravity field is much larger than the useful signal. This problem can be solved only by choosing a geostationary or a very distant from the Earth of the spacecraft orbit. However, it should be noted that just this fact allows to use the detector as an excellent gravity gradiometer for the investigation of the Earth gravity field.

It is necessary to take into account the fluctuations in the gravity gradient within the spacecraft, instability of the temperature of the solenoids, possibility of a "piezoeffect" in superconductors [4], [5], [6]-[8] and other measurement noises. As a result, we estimate the minimal relative shift of the solenoids available for the measurements as the magnitude of the order of $10^{-18}cm$.

We mean that the solenoids A and B are inside a superconducting shield.

Consider briefly the physical principles of the solenoids relative shift measurement caused by the gravitational-wave bursts. The idea is to measure the change in the proper magnetic flux of one of the solenoids by the SQUID attached to the solenoids. A superconducting quantum-interferometer device (SQUID) is attached to the solenoid and coupled to the other one inductively by a flux transformer. The results of the SQUID measurements are transmitted by radio by means of a conversion "voltage - frequency" and by using an isotropic active antenna. Such a method of the solenoids shift measurement is insensitive to micrometeorite impacts and other forces affecting the spacecraft.

5. Conclusion

The detector under consideration is a very promising device for gravitational waves and other gravitational space-based experimental projects. (See also the paper [9]). It is a technically difficult project that needs further detail study.

6. References

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